# Modifications and Future Plans for the TCS RMF FRC Facility

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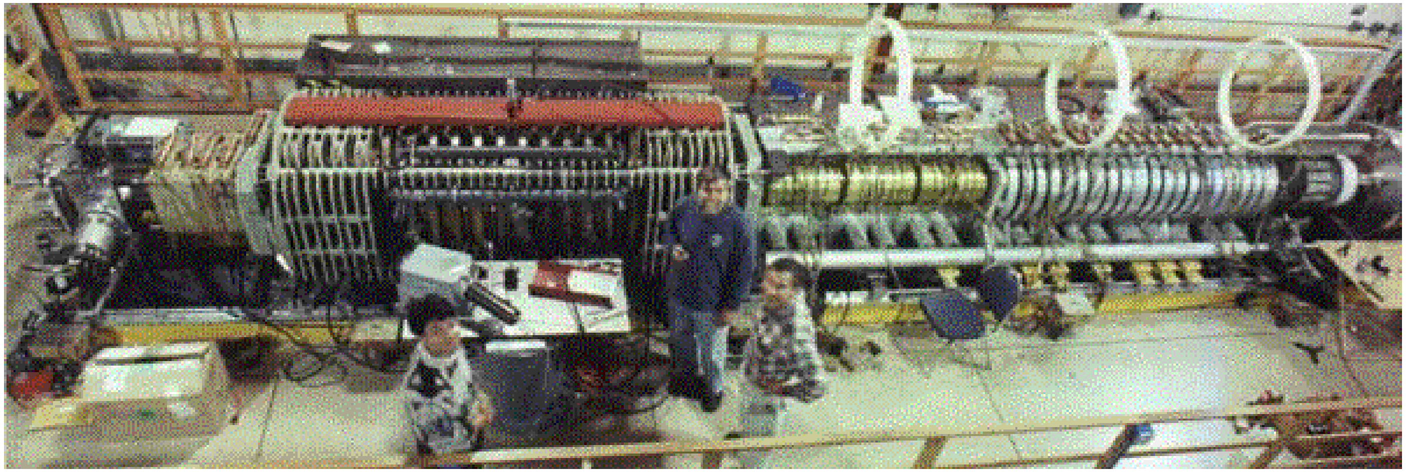
# Outline

- Previous TCS and overall performance
- TCS/mod
- Neutral Beam considerations
- Coaxial Slow Source addition

# TCS Facility

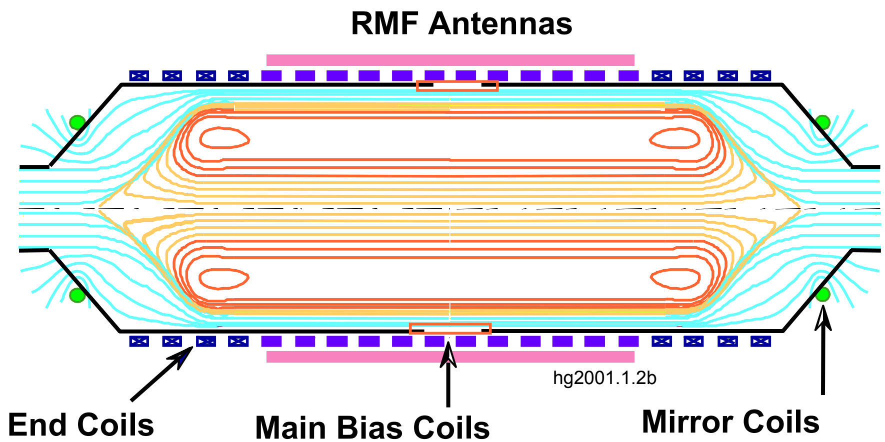
TCS
RMF generation & sustainment

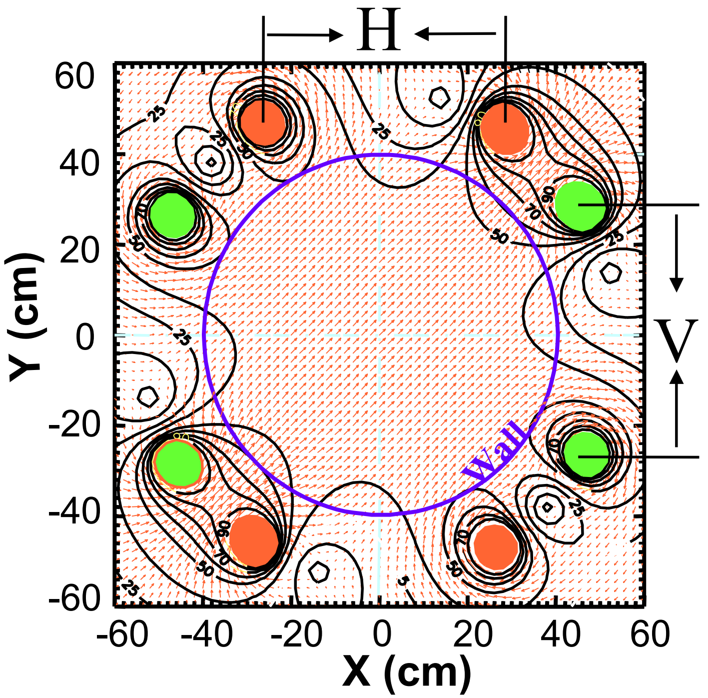
LSX/mod
(formation & ‘acceleration’)



- LSX/mod was half-size version of TCS to allow for acceleration section
- TCS utilized 2 of the 1.25-m long, 80-cm diameter LSX quartz tubes
- Joined with O-ring sealed plastic section for central diagnostic access

# Schematic of TCS Confinement Coils and RFM Antennas

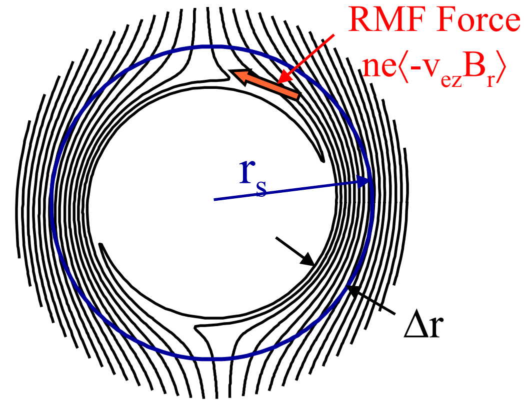



- Use of flux conserving coils yields $B_e = B_o/(1-x_s^2)$
- FRC will expand radially until limited by high $B_e$

# Standard Model of RMF Current Drive in FRCs

RMF ***self-consistently*** penetrates just far enough, $\Delta r \sim (B_e/\mu_o)/n_e e\omega r_s$ to maintain the diamagnetic current. Poloidal flux will increase as long as the RMF torque on the electrons exceeds the torque due to electron-ion drag (resistivity)




$$T_{RMF} = 2\pi r_s \ell_{ant}\left(B_\omega^2/\mu_o\right)\Delta r \qquad T_\eta = 0.5\pi\eta_\perp\left\langle n_e^2 e^2 \omega_e\right\rangle r_s^4 \ell_s$$

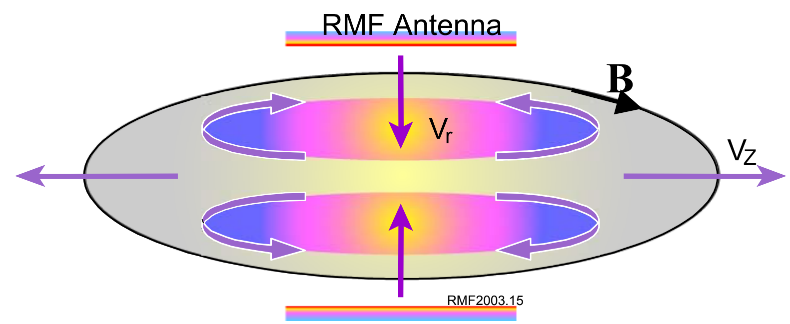
$$\boxed{\frac{d\phi_p}{dt} = 2\pi R E_\theta(R) = \frac{2}{n_e e r_s^2 \ell_s}\left(T_{RMF} - T_\eta\right)}$$

Equilibrium: $n_e \propto \dfrac{B_\omega}{\sqrt{\eta_\perp \omega r_s^2}}\left(\dfrac{\Delta r/r_s}{\omega_e/\omega}\right)$

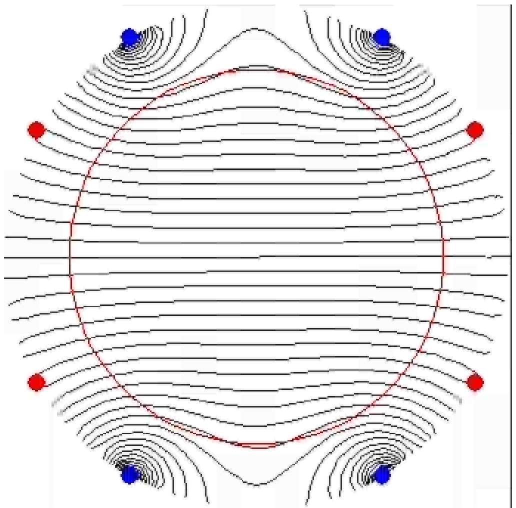
$B_e = B_o/(1-x_s^2) \propto (n_e T_t)^{1/2}$

$$E_\theta = \eta_\perp j_\theta + \left\langle -\tilde{v}_{ez}\tilde{B}_r\right\rangle + V_r B_z - V_z B_r$$

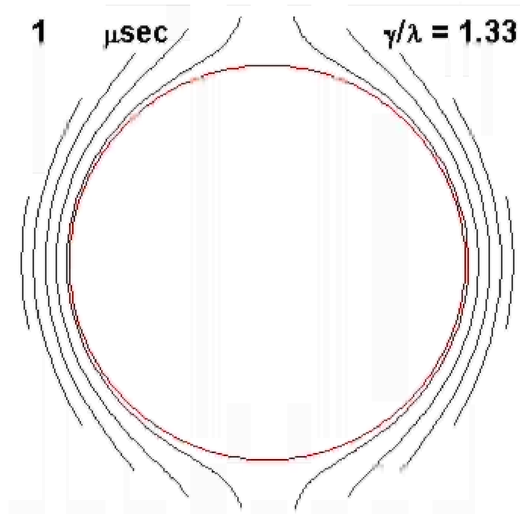
| | | | | |
|---|---|---|---|---|
| <u>Under Antenna</u> | | | | |
| Outer: | − | + | − | |
| Inner: | − | | + | |
| <u>FRC Ends</u> | | | | |
| Outer: | − | | + | + |
| Inner: | − | | + | + |



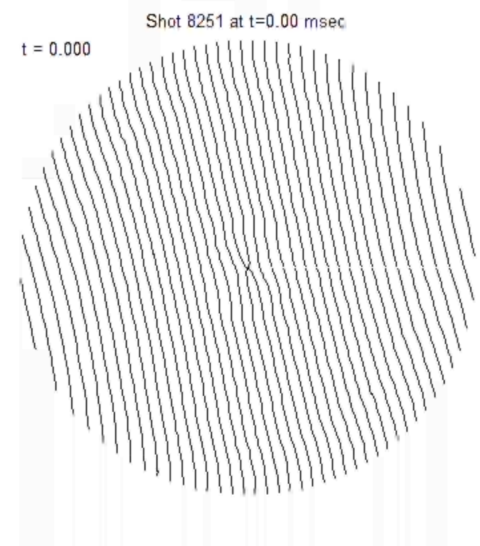
# RMF Penetration Movies



Vacuum **calculation** in lab frame of reference

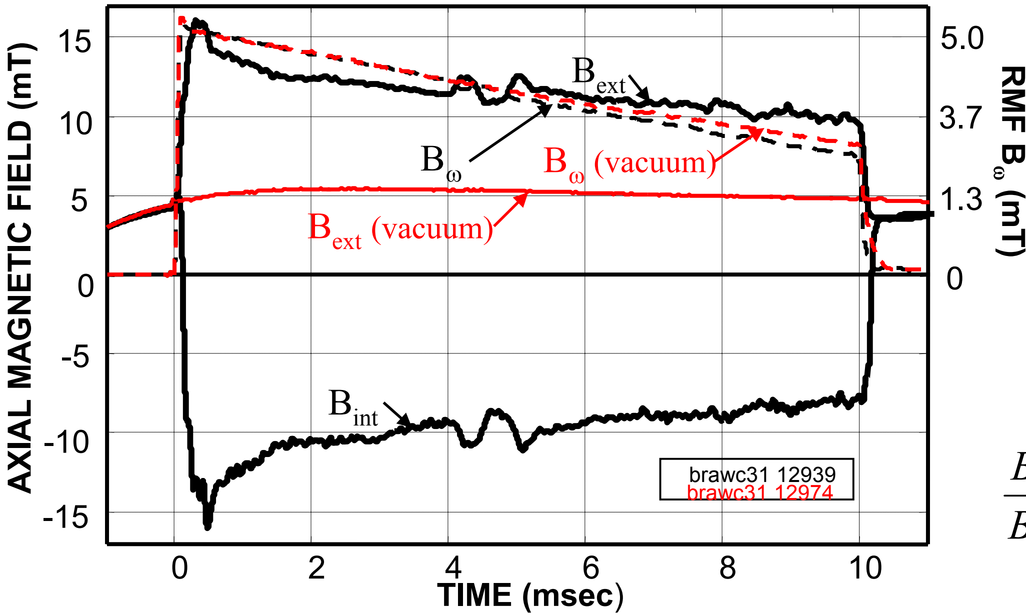



Plasma **calculation** in RMF frame of reference. (Calculation needs to start from already formed FRC)




Plasma **measurement** in RMF frame of reference

# Long Pulse Lengths Sustained by Recycling




For a Rigid Rotor profile

$$\frac{B_e}{B_\omega} = \left\{ \frac{\omega_{RR} r_s^2 (\Delta r / r_s)(\ell_a / \ell_s)}{4K_{RR} \tan K_{RR} (1 - \frac{1}{3} \tanh K_{RR}) \eta_{RR}} \right\}^{1/2}$$

- After first 0.5 msec, plasma conditions mostly independent of fill gas pressure (and to some extent composition).
- After ~4 msec, transition seen to higher performance mode (lower overall resistivity).
- No sign seen of tilting, but rotational n=2 distortion will develop due to overall RMF induced rotation as $B_\omega$ (*which provides strong inward stabilizing force*) decreases.

# Resistivities Inferred from Double RR Model

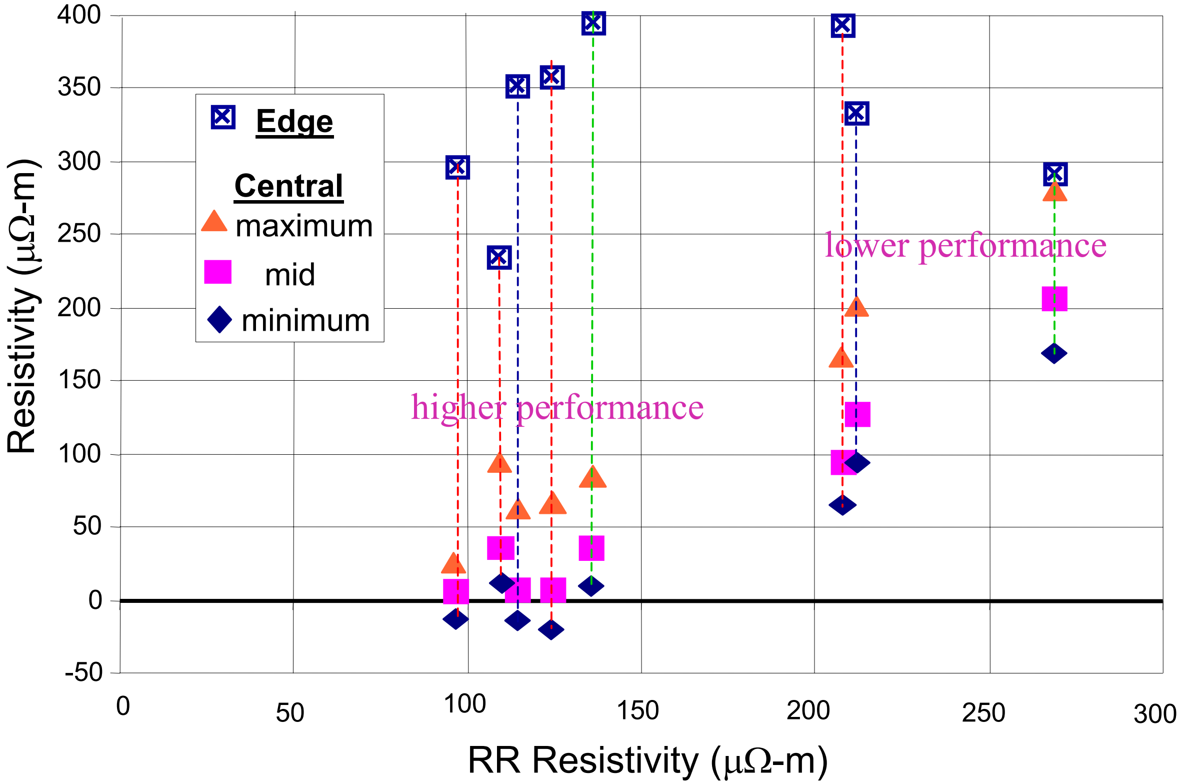
$$\eta_{RR} = \frac{B_\omega^2(\delta^*/r_s)(\ell_a/\ell_s)}{\tanh K_{RR}(1-\frac{1}{3}\tanh^2 K_{RR})n_m e B_e}$$

$$\eta_{pabs} = \frac{P_{abs\theta}}{2\pi \tanh K_{RR}(1-\frac{1}{3}\tanh^3 K_{RR})n_m e(B_e/\mu_o)r_s^2\ell_s}$$

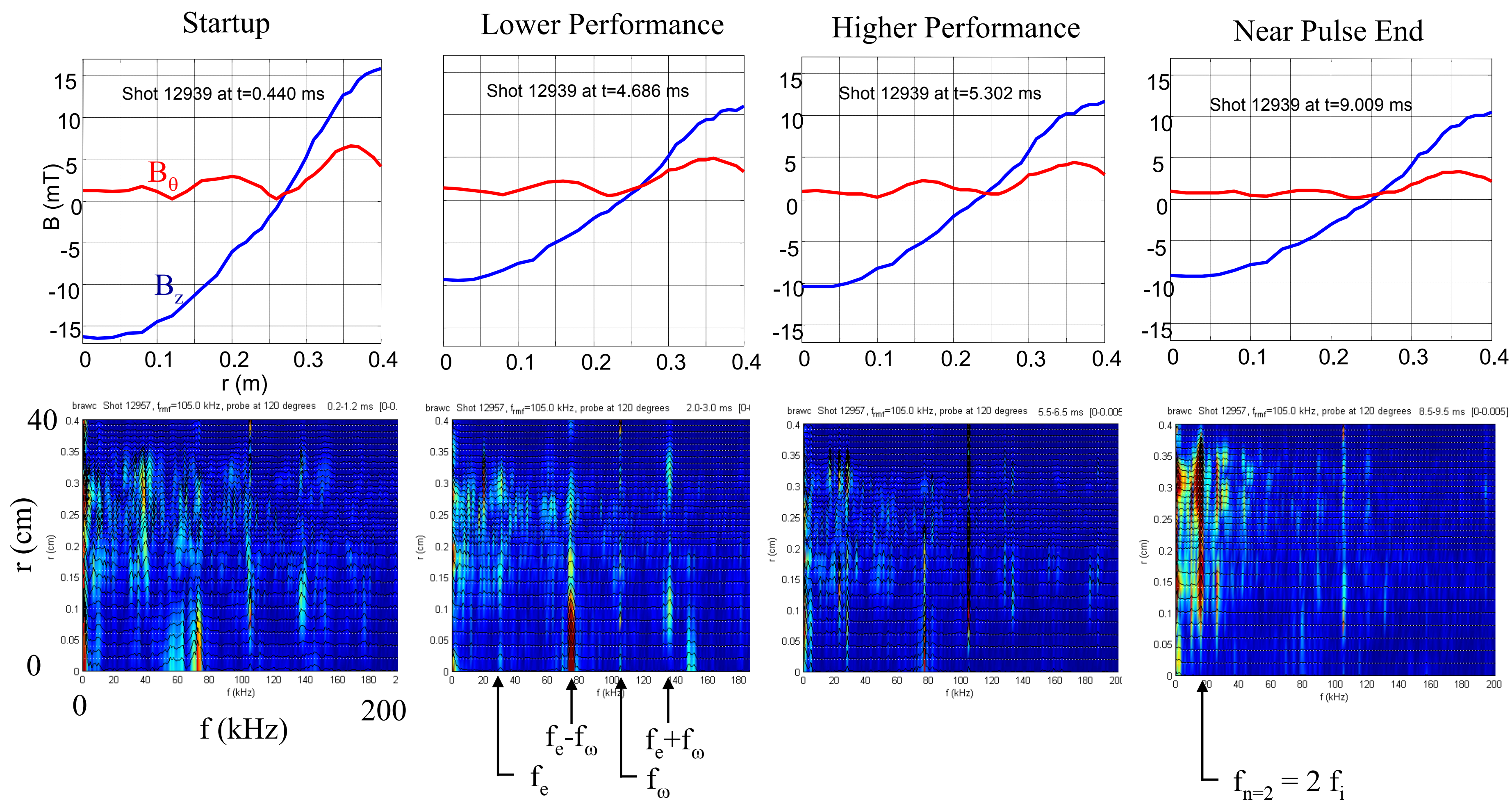
Data in red is high performance mode

| Shot | $\delta^*/r_s$ | $n_m$ ($10^{19}$m$^{-3}$) | $\eta_{RR}$ (μΩ-m) | $\eta_{pabs}$ (μΩ-m) | DRR Model: $\eta_{inner}$ (μΩ-m) | DRR Model: $\eta_{outer}$ (μΩ-m) |
|---|---|---|---|---|---|---|
| 12939 0.4 ms | 0.16 | 1.70 | 109 | 260 | 30 | 235 |
| 4.7 ms | 0.21 | 1.05 | 209 | 432 | 95 | 393 |
| 5.3 ms | 0.185 | 1.26 | 124 | 393 | **3** | **357** |
| 9.3 ms | 0.195 | 1.21 | 97 | 347 | **21** | **347** |
| 12889 6.3 ms | 0.23 | 0.95 | 269 | 425 | 204 | 291 |
| 7.0 ms | 0.18 | 1.10 | 136 | 345 | **28** | **394** |
| 12951 4.2 ms | 0.21 | 1.12 | 212 | 404 | 127 | 333 |
| 5.0 ms | 0.18 | 1.38 | 114 | 349 | **3** | **351** |

# Double RR Resistivity Values



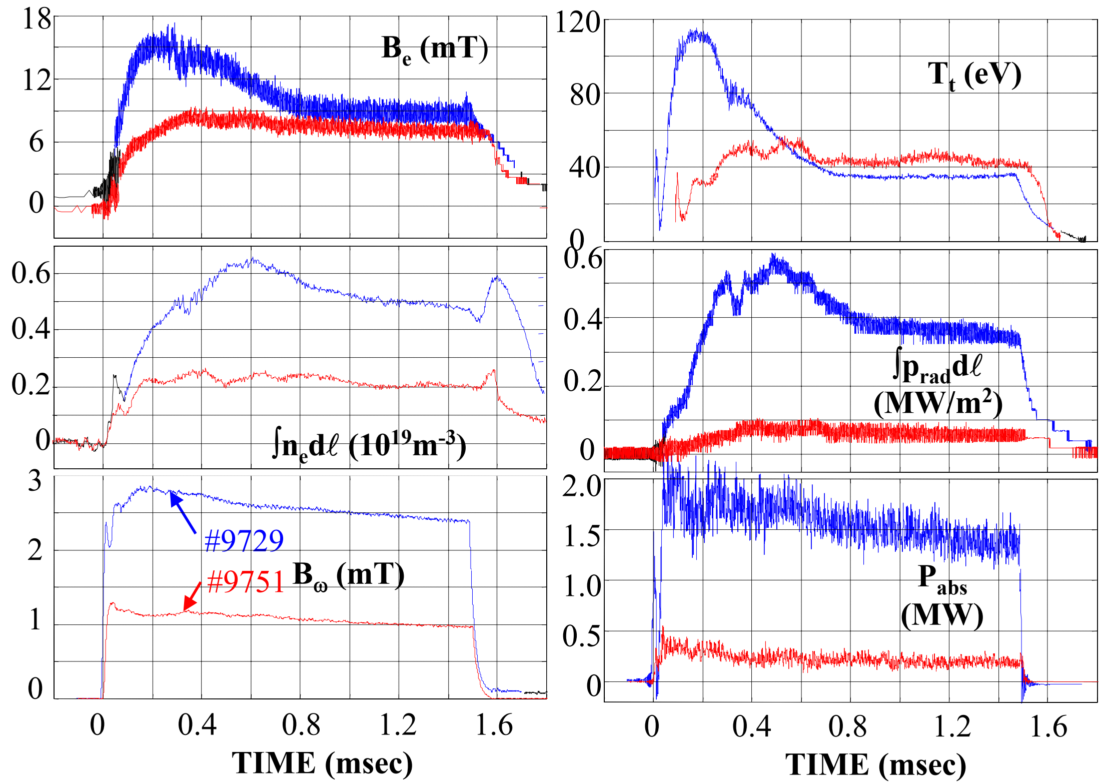
# Profile Changes & $B_z$ Frequency Content During Long Pulse Operation



# TCS Temperature (and Flux) Limited in Present Experiments – at least partially by impurities

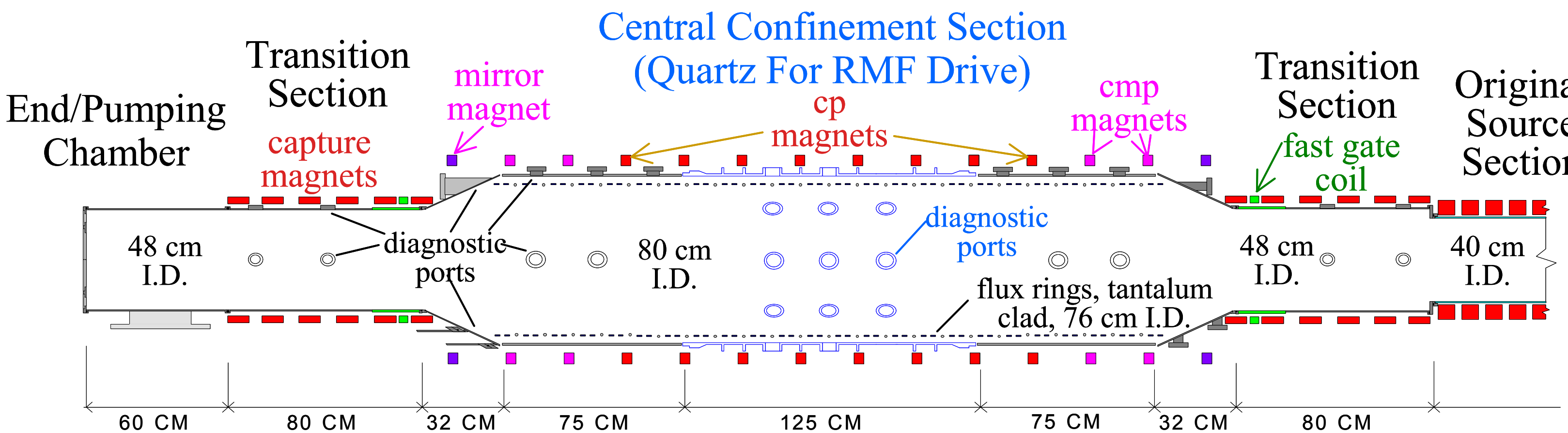
- Need to increase $\phi_p$ from ~2 mWb flux in TCS to ~6 mWb and $B_e$ from 15 to 50 mT for efficient TNBI trapping. This will happen automatically with RMF formation if temperature increases.

  - Applying more RMF power in present device results in initially higher $T_t$ and $B_e$. $n_e$ remains proportional to $B_\omega$, but temperature drops rapidly as $P_{rad}$ increases.




Operation at High $\omega = 1.62 \times 10^6\ s^{-1}$ and Low $B_\omega$

# Modifications Underway on TCS to Reduce Impurity Level and Radiative Losses




- Larger, metal input section to avoid translated FRC contact with quartz.
- Protective flux rings (possibly tantalum coated) under quartz RMF drive section.
- Elimination of “O-rings” to allow bakeout and discharge cleaning.
- Combination of Ti-gettering and wall conditioning (siliconization?).

Reduction of $P_{rad}$ will allow examination of non-radiatively limited $\tau_E$.

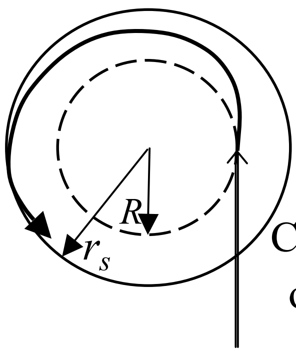
# Formation of High Beta Plasmas

- It is extremely difficult to form high $\beta$ plasmas if $E_{in}$ occurs on same timescale as $B_p^2/2\mu_o$ build-up. Plasma pressure must always track $B_p^2/2\mu_o$ and this can be mostly n rather than T unless thermal losses are small.
  - Impurity radiation imposes significant barrier to temperature rise below 100 eV.
  - Strong shock heating or fast resistive dissipation in theta-pinches, and to some extent in spheromak merging, can overcome this barrier.
- Rotating Magnetic Fields can form low density FRCs, but the 100 eV temperature barrier can only be exceeded if extreme care is taken in minimizing C and O impurities.
  - Theta-pinch formed, translated, and expanded FRCs can provide initial high temperatures if wall contact can be minimized.
  - Neutral beams can independently heat and sustain FRCs, but available powers are low.
- The Coaxial Slow Source (CSS) is an old idea for forming FRCs on slower timescales.
  - Since $P_{abs} \propto \eta(B_p/r)^2$ and $P_{rad} \propto n_{imp}n_e \propto f_i(B_p^2/T_t)^2$, if we rely on ohmic heating, the poloidal field must be increased slowly to give the temperature time to increase and avoid radiative collapse.
  - We can start at low density using RMF initiation.

# Tangential Neutral Beam Injection can Provide Current Drive near Field Null

- FRC must have sufficient flux to confine azimuthal high-energy ion velocity inside field null.
- Mostly axial injection can result in even larger excursions beyond separatrix, and will always result in wall contact for high $x_s$ FRCs.
- Tangential injection is most effective near, or slightly outside field null.
- High-energy ions will spread axially, even with minimal initial axial velocity component.

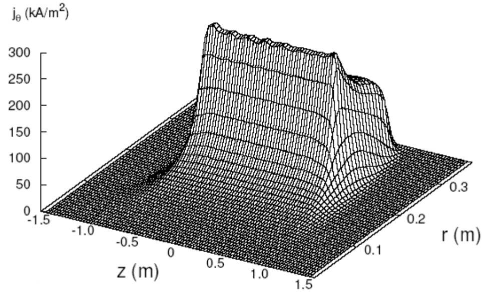
# TNBI near Field Null (Need about 5 mWb of flux)

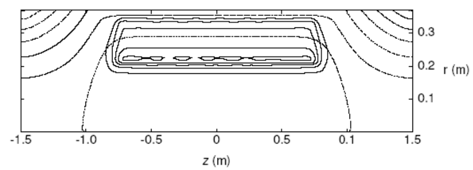


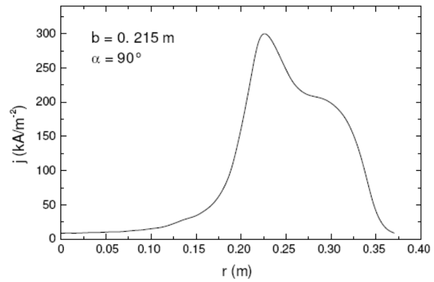

Critical orbit:

$$E_{ic}(\text{keV}) = \frac{0.0144}{A_i}\left(\frac{\phi_p(mWb)}{r_s(m)}\right)^2$$

Ideal energies < $E_{ic}$, but can operate with $E_i \sim 2E_{ic}$.



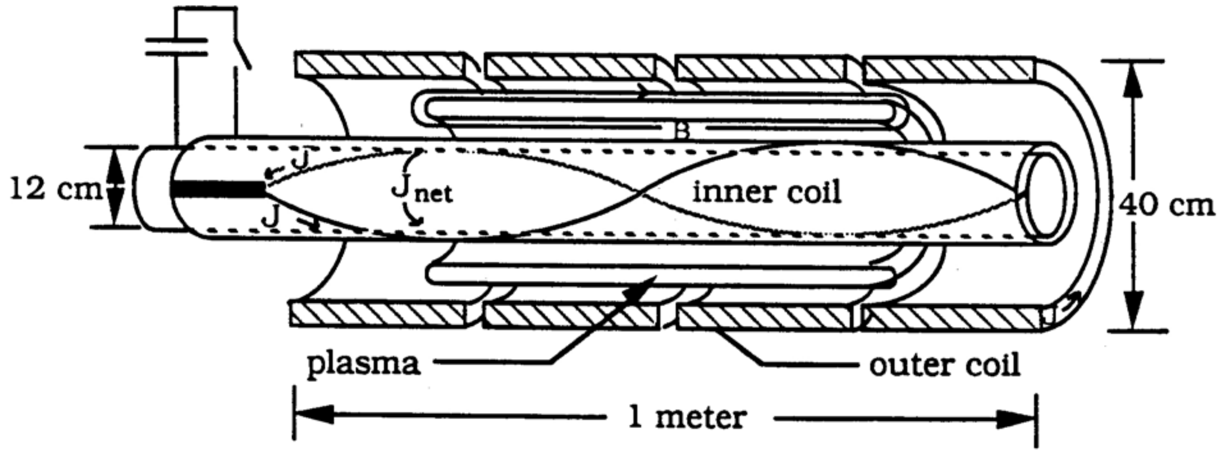




10 keV ($2E_{ic}$) TNBI calculations by Ricardo Farengo to set immediate TCS/mod goals. Nuclear Fusion **44**, 1015 (2004).

| | TCS/mod goals | 'Reactor' |
|---|---|---|
| $\phi_p$ (mWb) | 6 | 3000 |
| $B_e$ (T) | 0.08 | 1.2 |
| $r_s$(m) | 0.3 | 2.0 |
| $T_e$ (keV) | 0.14 | 10 |
| $n_e(10^{20}\ m^{-3})$ | 0.5 | 1.0 |
| $A_i$ beam | 1 | 3 |
| $E_i(r_s)$ | 25 keV | 100 MeV |
| $E_{ic}$ | 5 keV | 20 MeV |

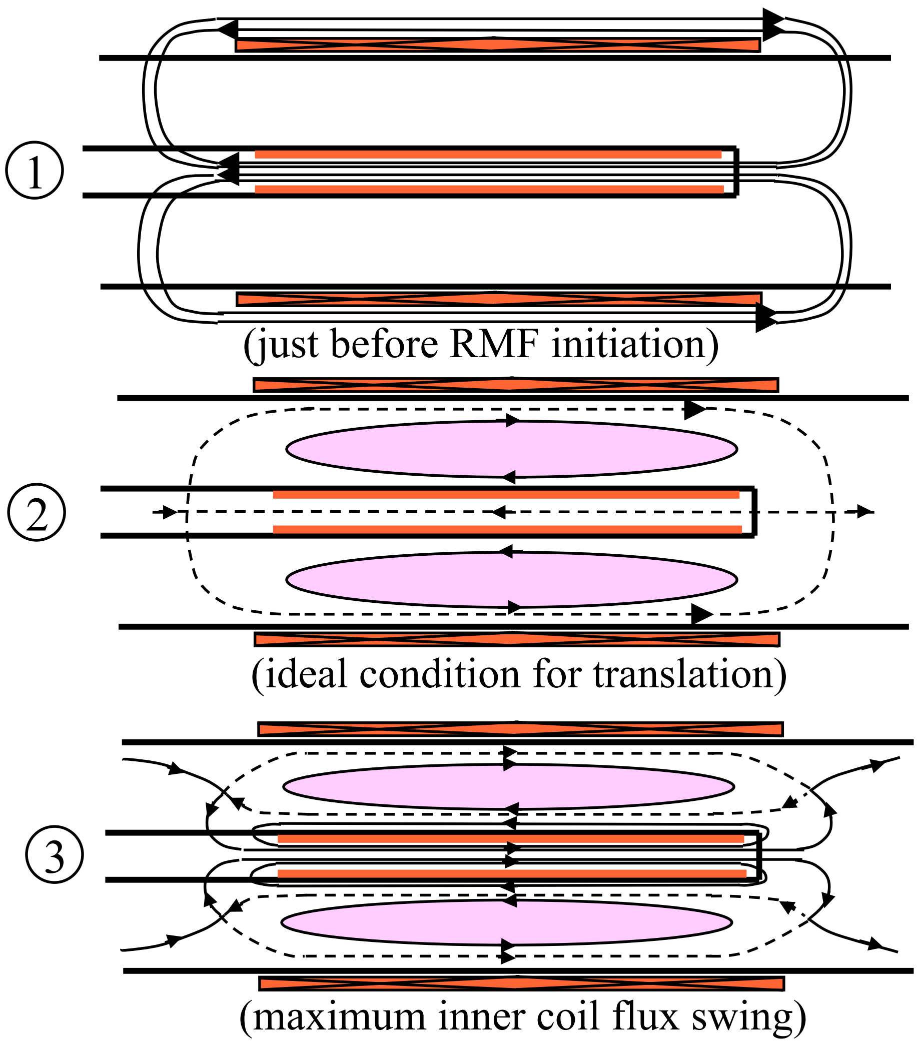
$\phi_p \sim 2$ mWb in present TCS

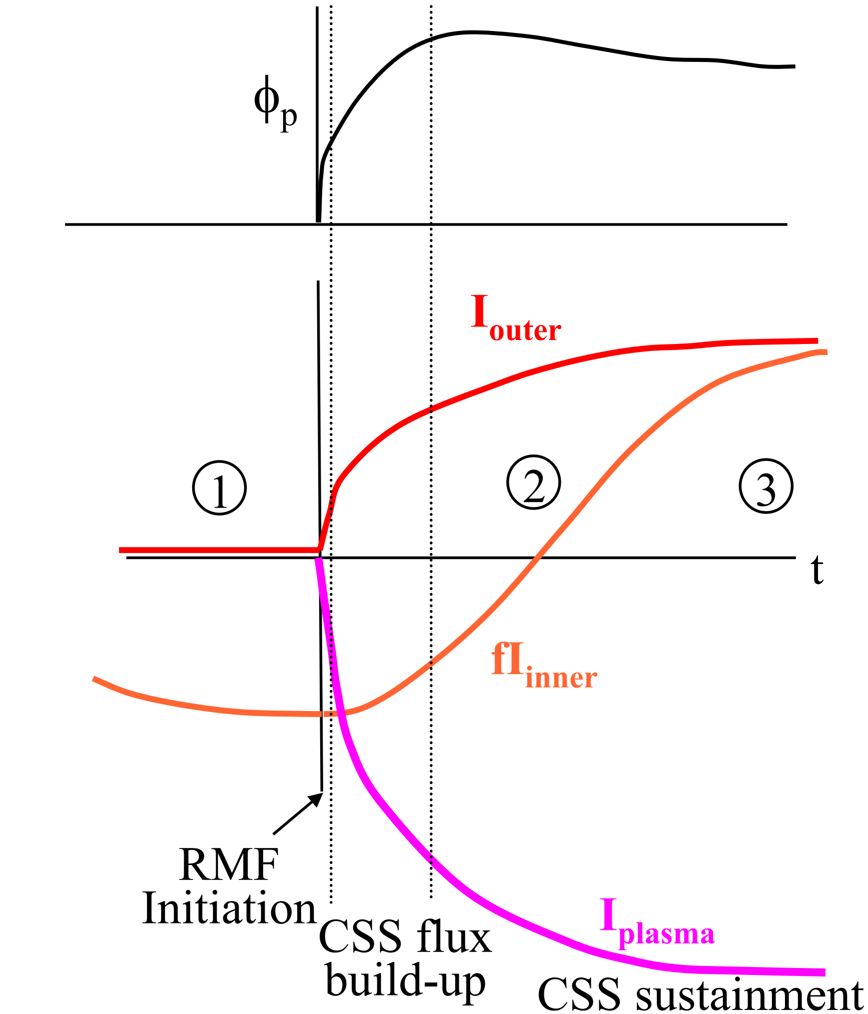
# Coaxial Slow Source (CSS) can Add Energy and Increase Flux.



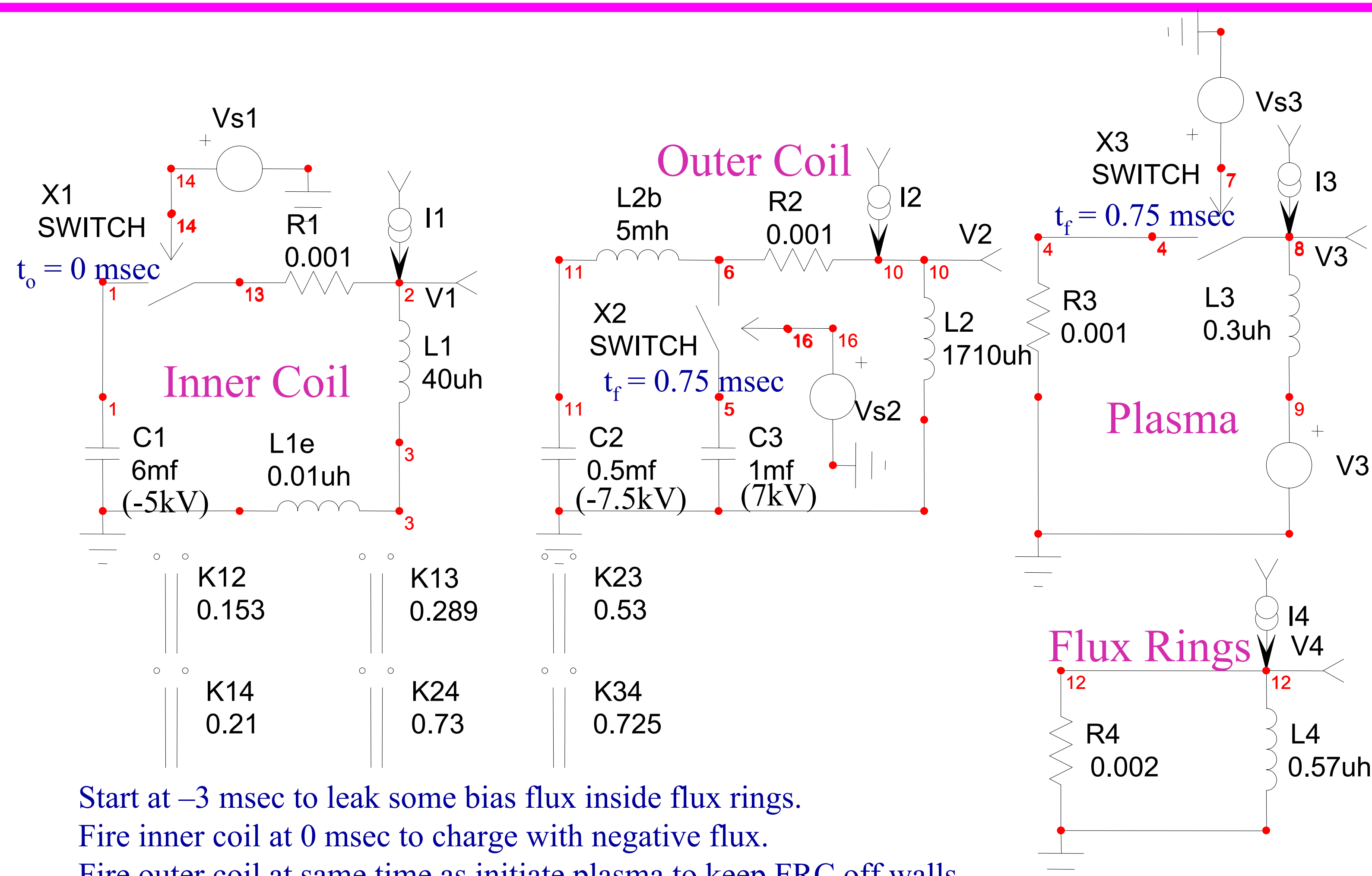

- Two Modes of Operation:
  - Fast, high voltage: $t_{1/4} << \tau_{L/R}$ of FRC.
    - » All inner coil flux will be transferred to FRC.
  - Slow, multi-turn coils: $t_{1/4} >> \tau_{L/R}$ of FRC.
    - » FRC current will be equal to $(V/N)_{coil}/R_{FRC}$.

# CSS Flux Build-Up & Sustainment of RMF Generated FRC



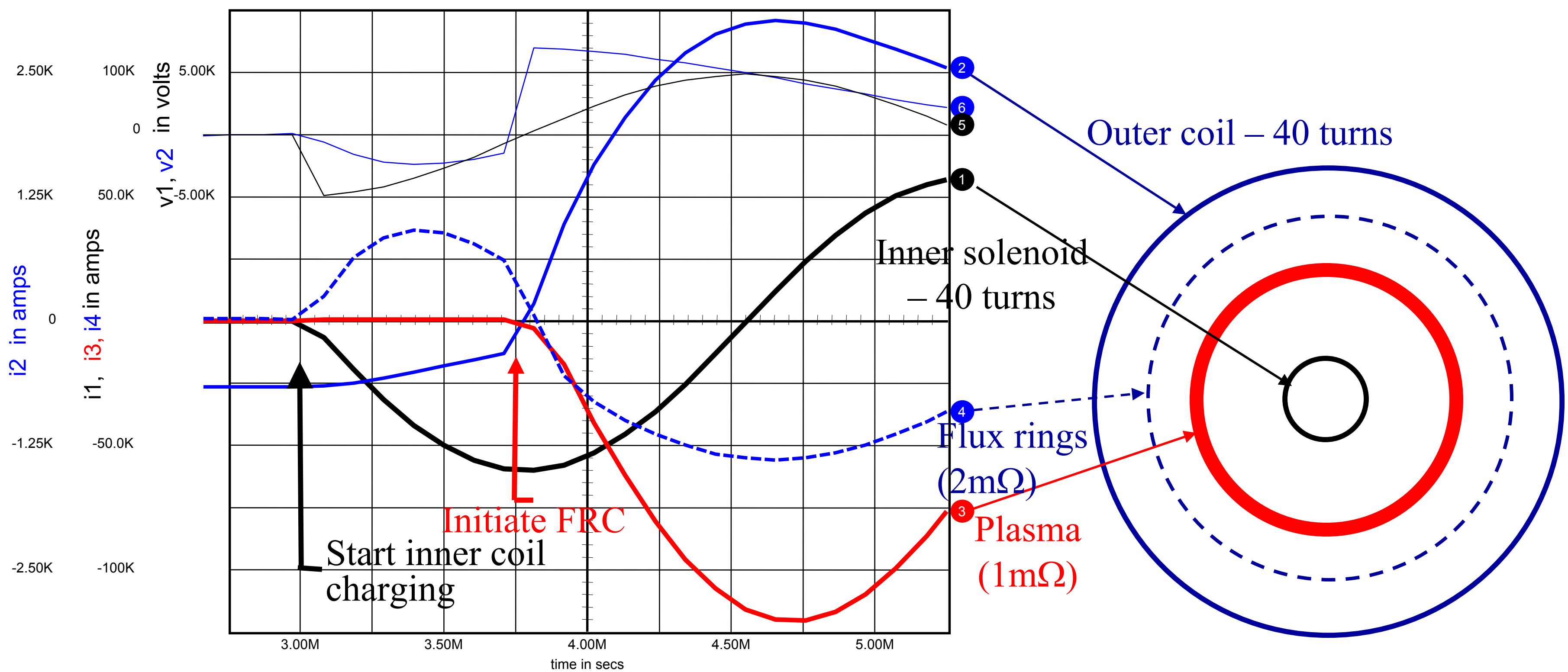



# SPICE Circuit Modeling




Start at –3 msec to leak some bias flux inside flux rings.
Fire inner coil at 0 msec to charge with negative flux.
Fire outer coil at same time as initiate plasma to keep FRC off walls.

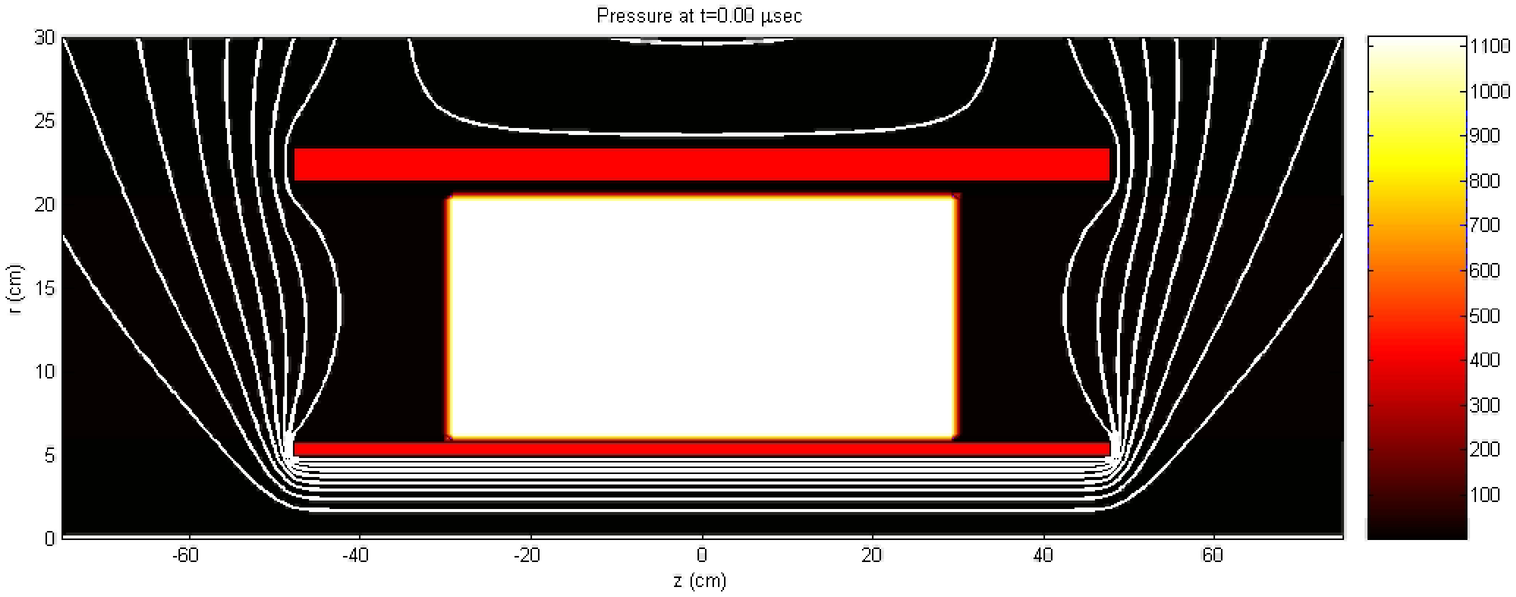
# SPICE CSS calculation for 1 mΩ FRC driven by 40-turn, 5 kV solenoid




Initial bias ($I_2$) applied so that there is ~zero field inside flux rings at time of plasma initiation.

125 V/turn generates ~125 kA in 1 mΩ FRC. Applied power ~15 MW. Equilibrium field ~ 75 mT and equilibrium flux ~20 mWb

# CSS 2-D Calculation



# Summary

- TCS has formed and maintained FRCs using RMF, but the radiation levels are high and the temperatures low.
- RMF drive results in high FRC edge resistivities, but may be very useful for stabilizing instabilities and producing low interior resistivities. *It is probably not a stand alone current drive mechanism*.
- TCS/mod is being constructed to provide a clean, bakable vacuum system.
- Both TNBI and flux core additions are being considered for future utilization.